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THESIS

MEDICAL REMOTE SENSORS IN TACTICAL NETWORKS

by

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March 2015

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LIST OF ACRONYMS AND ABBREVIATIONS

BSN	body sensor network
CCA	clear channel assessment
CENETIX	Center for Network Innovation and Experimentation
COTS	commercial off-the-shelf
CSMA/CA	sense multiple access with collision avoidance
DOD	Department of Defense
ECG	electrocardiogram
EHR	electronic health record
FFD	full-function device
GAO	Government Accountability Office
HA/DR	humanitarian assistance and disaster relief
IEEE	Institute of Electrical and Electronics Engineers
IOS	International Organization for Standardization
IoT	Internet of Things
ISM	industrial scientific and medical
IT	information technology
JTTS	Joint Theater Trauma Registry
MAC	Media Access Control
MEDIVAC	medical evacuation
MEMS	microelectromechanical systems
MTF	military treatment facility
NFC	near field communication
OSI	open systems interconnection
PAN	personal area network
PDA	personnel digital assistant
RF	radio frequency
RFD	reduced-function device
RFID	radio-frequency identification
RID	radio interface device
SpO2	oxygen saturation

TCCC	tactical combat casualty care
UHF	ultrahigh frequency
USAR	urban search and rescue
WBAN	wireless body area network
WPAN	wireless personal area network
WSN	wireless sensor network

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LT Gabriel R. Urquidez, MSC, USN

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LT Hunter R. Coates, MSC, USN

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I. INTRODUCTION

The U.S. Coast Guard and Department of Defense (DOD) operate as first responders in emergency, natural disaster, and combat environments. These unique environments provide challenging communication situations for healthcare providers during medical triage in which weather conditions, lack of infrastructure, and combat operations exacerbate the communication breakdown of vital sign data commonly found during medical evacuations (MEDIVACs). Few electronic administrative options exist at the tactical level for communicating vital signs; as a result, first responders utilize pen, paper, and audio mediums to communicate patient data (Blackbourne, 2011). These historical means of communication, however, have been shown to be ineffective and error prone (Eastridge et al., 2011). An alternative to this manual process is automation of the vital sign process acquisition and transmission with the application of biosensors. Recent advancements in commercial off-the-shelf (COTS) monitoring devices offer new alternatives to wireless monitoring of vital signs and may offer a solution for transcribing and recording accurate vital sign data.

A. BACKGROUND

The communication and information problem in medicine can have wide impactful effects outside the clinical setting. Historically, healthcare providers who lack information and distrust verbal or medical documentation acquired on scene resort to ordering duplicate tests and re-administering medications when dealing with the patients arriving with unknown medical histories (Kripalani et al., 2007). Can technology provide a better alternative to the current process of monitoring and transcribing medical data? If healthcare providers can access patient medical histories before, during, and after the patient arrives at a treatment facility for care, would the continuum of care lead to increased efficiency and patient survivability? We say yes and propose that the answers may lie in recent advancements in wireless sensor technology.

While recent advances in wireless network infrastructure have increased bandwidth and connection capabilities in a wide assortment of technological platforms, the development of the sensor is vital. The sensor must meet the physical and software requirements of being small enough not to be burdensome for the user and yet technologically powerful enough to transmit appropriate data—all while attaining an above average battery life (Hirschberg, Betts, Emanuel, & Caples, 2014). The miniaturization of sensors and advances in network infrastructure for remote monitoring is regarded by many medical information technology professionals as the core technology needed for the realization of real-time information sharing (Abuan, 2009). By utilizing existing cellular, Wi-Fi, and tactical network infrastructures with low-power network devices such as Bluetooth® and near field communications (NFCs), health monitoring is extending outside the traditional clinical setting. The use of wearable sensors in remote and harsh environments, such as on Ebola patients in sub-Saharan Africa or during search and rescue operations in frigid ocean waters, would allow providers to access real-time medical diagnostic data remotely. Leaders, for the first time, would have diagnostic data on personnel health status, which could affect operational tempo in such environments as naval boarding parties, special warfare, radiological, biohazard, humanitarian assistance and disaster relief (HA/DR). Little research has been done on wearable sensor capabilities for use within military tactical networks. In this thesis, we present our research on the current capabilities of COTS sensor technologies for monitoring vital signs and explain the challenges presented by using wireless technologies to transmit this crucial data.

B. FOCUS ON VITAL SIGNS

Sensor adaption within medicine is growing in popularity due to its accuracy in recording data and its boundless reach (Chan, Liang, & Lin, 2014). Vital sign monitoring has traditionally been a static endeavor requiring medical personnel to perform clinical assessments at the bedside. These assessments require physical interaction between the provider and the patient and generally cover pulse, temperature, respiration rate, and blood pressure. Depending on the severity of the patient’s condition, vital signs monitoring may need to be conducted daily, hourly, or by the minute. The average time

needed to perform these assessments ranges from one to two minutes (Chan et al., 2014). To increase provider efficiency and correct the large amount of man-hours lost to continuous monitoring, many health care organizations have instituted machine-assisted vital signs monitoring. These machines, usually found at the bedside in a hospital or clinic setting, are large and bulky and require hard lines to be connected to the patient. This current setup highlights two unintended, but significant consequences of manual vital sign practice: limitation of range and user transcription errors.

Limitation of Range

The current state of computer-assisted vital signs monitoring found in operational and hospital settings are limited to hard-wire connections to the patient and power source (Kripalani et al., 2007). In many cases, the hospital vital sign systems are stand-alone systems, which actively monitor, but lack any recordable means that can be transferred to a central database. Although computer-assisted vital sign machines have improved efficiencies in the physical process of acquiring vital signs, the limited range requires patients to be monitored in the presence of a health provider.

Transcription Problems

The inability to automatically capture and transcribe vital signs forces providers to routinely transcribe the same vital signs data multiple times. For example, in emergency situations, first line responders commonly record vitals data on disposable gloves and, when transferring the patient, verbally recite the data to the receiving treatment team. Generally, this method of transferring information results in inaccurate or missing medical histories (Kripalani et al., 2007).

C. EVIDENCE OF NEED

The Surgeon General of the Navy’s 2015 enabling objective is to capitalize on information technology to improve the health and readiness of the fleet (Navy Medicine, 2015). More specifically, the Surgeon General’s underlying goal is to develop and implement systems that share medical information across multiple interfaces by feeding data into each individual’s electronic health record (EHR) see figure 1. The intent is to

discover a way for information to be exchanged jointly between providers on multiple platforms to improve healthcare efficiencies and provider responsiveness in caring for the warfighter. Previous studies have shown vital sign monitoring and recording is a prime candidate for technological integration, as the current process of manually recording is costly, inefficient, and error prone (Slight et al., 2014). Improving military medicine by leveraging technology is not a new concept.

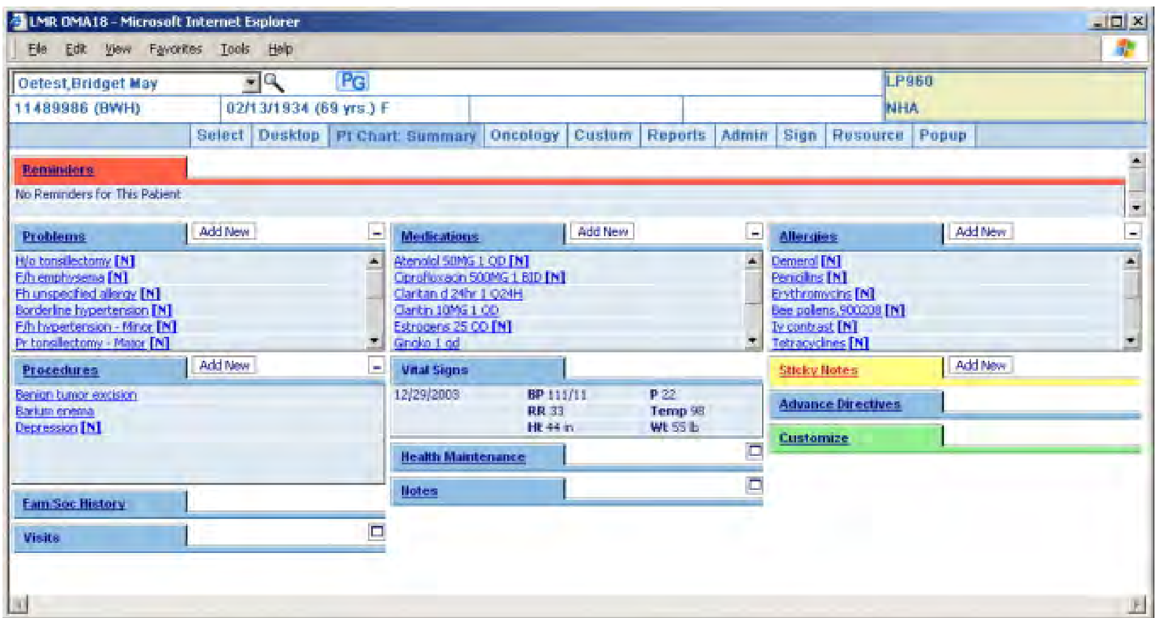


Figure 1. Typical dashboard of most EHR systems (from Pizziferri et al., 2005).

In 1996, after Operation Desert Storm, the Government Accountability Office (GAO) issued a scathing report on the shortfalls of wartime medical care (GAO, 1996). In the report, the GAO noted nine military medicine procedures that failed to provide adequate medical support. Of those nine identified, three were related to information technology (IT) communications, computers, and information management. The corrective actions stressed by the GAO were "incorporating technological advancements and equipment modernization, to compete with the movement of combat troops and other war-fighting materials to the theater" (GAO, 1996, p.5). Since that report, leaders in military medicine have investigated numerous IT initiatives to improve battlefield

medicine with the hope of developing a systematic and integrated approach to better organize and coordinate battlefield medicine. Some IT initiatives that made a debut over the years include the 1998 Composite Health Care System (first clinical computer module), the 2004 Armed Forces Health Longitudinal Technology Application (first EHR), and the Joint Theater Trauma Registry (JTTS) (a database of all operational battlefield injuries). The goal to minimize morbidity and mortality in military operations remains the primary focus of military medicine, and the use of wireless sensor adaption for monitoring vital signs may be the next technological step.

D. METHODOLOGY

We used a qualitative research method emphasizing case studies and literature review to explore the viability of COTS sensors for monitoring vital signs within mesh networks utilizing TrellisWare tactical radios. The concept of wireless sensor adaption to monitor vital signs in medicine is quickly gaining traction in the civilian sector, and studies to adapt wireless sensors in the military are limited. Through our baseline study, we intend to provide a foundational analysis of issues associated with acquiring, storing, forwarding, and acting upon critical vital sign data.

E. PURPOSE OF STUDY

The purpose of this study is to explore the current capabilities of COTS sensor technologies for monitoring vital signs. Wearable sensors provide the opportunity to project personnel vital signs in noncovert missions such as boarding parties, mass casualties, preventative medicine, search and rescue, and pandemic disease outbreaks. Vital sign information transfer has historically been limited to verbal- and paper-based methods. These methods are prone to error and increase the risk of transcriptions being absent from medical histories, which has been shown to impact later treatment options (Blackbourne, 2011). Utilizing wearable sensors in tactical networks to automate vital sign data may offer a solution to this problem. Sensor research is needed to adequately determine the state of current sensor capabilities within the DOD tactical network infrastructure. The thesis seeks to answer the following questions:

- What are pertinent vital sign information needs for adequate sensor application?
- Which Institute of Electrical and Electronics Engineers (IEEE) standards are best suited for wireless sensor's transmitting vital sign data?
- Can the COTS product BioHarness 3 connect to a tactical mesh network utilizing TrellisWare radios?

F. CHAPTER OUTLINE

This thesis is organized into five chapters:

Chapter I provides an introduction to the problem and purpose of research.

Chapter II is a discussion of the literature review associated with vital signs and previous sensor study applications.

Chapter III provides an overview of how sensors communicate over a wireless medium.

Chapter IV is a discussion of observations of the BioHarness 3 sensor integration into a wireless mesh network.

Chapter V summarizes the information discussed in the previous chapters and concludes with recommendations.

II. ANALYSIS OF SENSOR CAPABLITIES

Sensor adaptation in medicine has begun to gain traction in both the private and public medical industries as a viable technological platform for addressing a myriad of problems (Topol, Steinhubl, & Torkamani, 2015). Chief among these problems is the monitoring and recording issue in patient care that centers on the historical inability to accurately monitor and transcribe medical data from one medium to another (South, Skelley, Dang, & Woolley, 2015). Multiple studies have addressed the issue, but very few have presented wireless remote sensors in tactical networks as a solution. Our analysis seeks to bring better understanding of the monitoring and recording problem by exploring sensor adaption capabilities within military medicine.

A. DATA SOURCES AND SEARCH STRATEGY

We performed multiple searches utilizing Google Scholar, PubMed, and IEEE databases. Google Scholar returned 2.3 million results for the term *body sensor*. When we narrowed the range to the years 2014 and 2015, the search returned 21,500 results. When we searched PubMed for *body sensor networks*, we found an increasing number of peer-reviewed articles, from three in 1971 to 338 in 2014. Other searches included *vital sign networks*, *military vital sign weaknesses*, and *vital sign impact on treatment*. When we narrowed our Google Scholar search to peer-reviewed articles and excluded patents, the number of results dropped from 2.3 million to two million. Narrowing our search to the years 2014 and 2015 caused the results to decrease to 17,900. We focused our research primarily on articles published between 2005 and 2015, with the exception of historical articles that we used to determine past vital sign processes. This search strategy provided ample information for understanding the impact of vital signs in patient care.

B. THE IMPACT OF VITAL SIGNS

The first step to understanding how remote sensors in tactical networks can impact the communication of vital signs is reviewing current vital sign monitoring and documentation processes. When conducting this analysis, we found the prevalent conclusion of most studies was the lack of any suitable IT solution for patient monitoring

and accurate data transcription. Regardless of the environment (e.g., hospital, clinic, remote, or shipboard medicine), the consensus from the literature was that current technological advances in patient monitoring were inconsistent at best. Attempts to apply sensor solutions have focused on EHR and automated vital signs machines (Du, Yang, Liao, Liu, & Liu, 2014). However, inaccuracy in the transfer of medical information from automated machines into EHRs continues because providers are manually recording vital signs from a machine onto paper, and then manually entering the data into a computer (Smith, Banner, Lozano, Olney, & Friedman, 2009). As noted in the article "Connected Care: Reducing Errors through Automated Vital Signs Data Upload," the manual transcription process of vital signs by providers increases the risk of omission and errors in health records (Smith et al., 2009). The current transcription process contains unnecessary risks that can have adverse effects on patient care, considering that vital signs "are perhaps the most fundamental component of patient evaluation. They provide the basis for clinical decision making regarding treatments, interventions, progress, and discharge" (Smith et al., 2009, p. 318).

An example of the impact vital signs can have on clinical decisions is highlighted in the 2009 study documenting the H1N1 influenza outbreak among military healthcare beneficiaries in San Diego (Crum-Cianflone et al., p. 1805). The outbreak consisted of 761 patients who presented to the hospital with influenza-like symptoms. Of those patients, 97 were confirmed positive for H1N1. On physical examination, providers found patients suspected of having the H1N1 virus were universally febrile (>97.1 degrees Fahrenheit [F]). The information the temperature vital sign provided was the determining factor for early detection of H1N1, which is the earliest indicator the body is actively fighting infection. This information allowed providers to implement isolation procedures and don personal protective equipment to contain the spread of the virus. After the event, providers reviewed patients' medical records and found many of the records contained errors or omissions of early vital signs data. These inaccuracies seem to stem from the use of verbal or handwritten processes for relaying patient data from one medium to the next (Crum-Cianflone et al., 2009, p. 1809).

In the *Journal of Healthcare Information Management*, Gearing and Olney (2005) describe the transcription problem as an over-duplication issue. They argue the habitual use of paper for recording vital signs leads to an increase in chance for error. In their study of patients in a hospital ward, they found that from initial documentation to final data entry into an EHR, vital signs could be re-transcribed as many as three times for each provider encounter. If patients have their vital signs taken every four hours and a provider sees 30 patients in a day, as many as 900 opportunities for error are possible in a single shift. These numbers include omission or potential transcription errors, such as 100.7 degrees F being transcribed as 107.0 degrees F (Gearing et al., 2005).

If not done correctly, the physical process of acquiring and documenting vital signs can lead to adverse response by providers for timely care. Cioffi, Salter, Wilkes, Vonu-Boriceanu, and Scott (2006), in their study of a hospital's emergency department, found that inadequate documentation was one of the main reasons clinicians failed to respond to patients with abnormal vital signs. For Gearing et al., (2005), the key to solving the monitoring and documentation problem is leveraging technology and documenting vital signs data only in an electronic medium. In their study comparing the entry of vital signs in a paper record versus an EHR, the researchers had clinicians document vital signs in a paper-records format only and then in an EHR only. Researchers found the error rate for electronic vital signs documentation was less than 5% compared with the paper chart error rate of 10%. Thus, providers who used an electronic medium for documentation reduced the rate of vital sign entry errors in EHRs by more than half (56%) (Gearing et al., 2005, p. 45). The process in this study, however, still utilized manual data entry, with nurses recording vital sign data on paper charts and then transcribing them via data entry into an EHR. A better method would utilize vital sign machines that could send data to an EHR automatically.

In the study, "Connected Care: Reducing Errors through Automated Vital Signs Data Upload," researchers compared a previous baseline study that determined that error rates for vital signs captured on plain paper transcribed into a paper chart were 10% (Smith et al., 2009). In an effort to improve this error rate, utilizing a personnel digital assistant (PDA), the researchers conducted a separate test to wirelessly transmit vital

signs data directly into an EHR. The data were automatically transmitted via hard wire to electrodes hardwired onto a patient via body patches. Researchers reviewed 1,514 sets of vital signs collected electronically for accuracy and compared the error rate with data from the manual process. They found the automated upload of vital signs directly into an EHR reduced the documentation error rate to less than 1% (Smith et al., 2009). This rate represented a significant reduction in vital sign documentation errors with the use of mobile technology when compared with traditional charting methods ($P<.001$). The results of this study, conducted in the closed environment of a hospital ward, demonstrate the potential benefits automatic communication can have on the monitoring and documentation of patients.

C. UNDERSTANDING THE MILITARY MEDICAL NEED

Prehospital trauma care performed in the battlefield differs markedly from that performed in the civilian sector. Treatment guidelines developed for the civilian setting do not necessarily translate well to the military and may result in preventable deaths and unnecessary additional casualties if the tactical environment is not fully considered. Vital to preventing deaths is addressing the shortcomings of technology in monitoring and documenting patient care in the battle space.

In the study "1831," Army physician COL Lorne Blackbourne (2011) compared the monitoring and treatment technologies available in the battlefield in 1831 to those in 2010. He found that while technology had advanced in numerous fields of medicine and military operations, communication of basic medical vital sign data remained tethered to the pen-and-paper technology that existed in 1831. He reasoned medical information was not transferring with patients from the battlefield because documenting in the field took too much time of the medics who were administering treatment. The inability to document vital signs resulted in missing prehospital data.

Figure 2. A Navy corpsman yells to communicate with a fellow corpsman as he tends to a patient behind a noisy CH-53 helicopter (from http://www.stripes.com/news/31st-meu-s-nightingale-team-trains-to-respond-to-emergencies-1.37740).

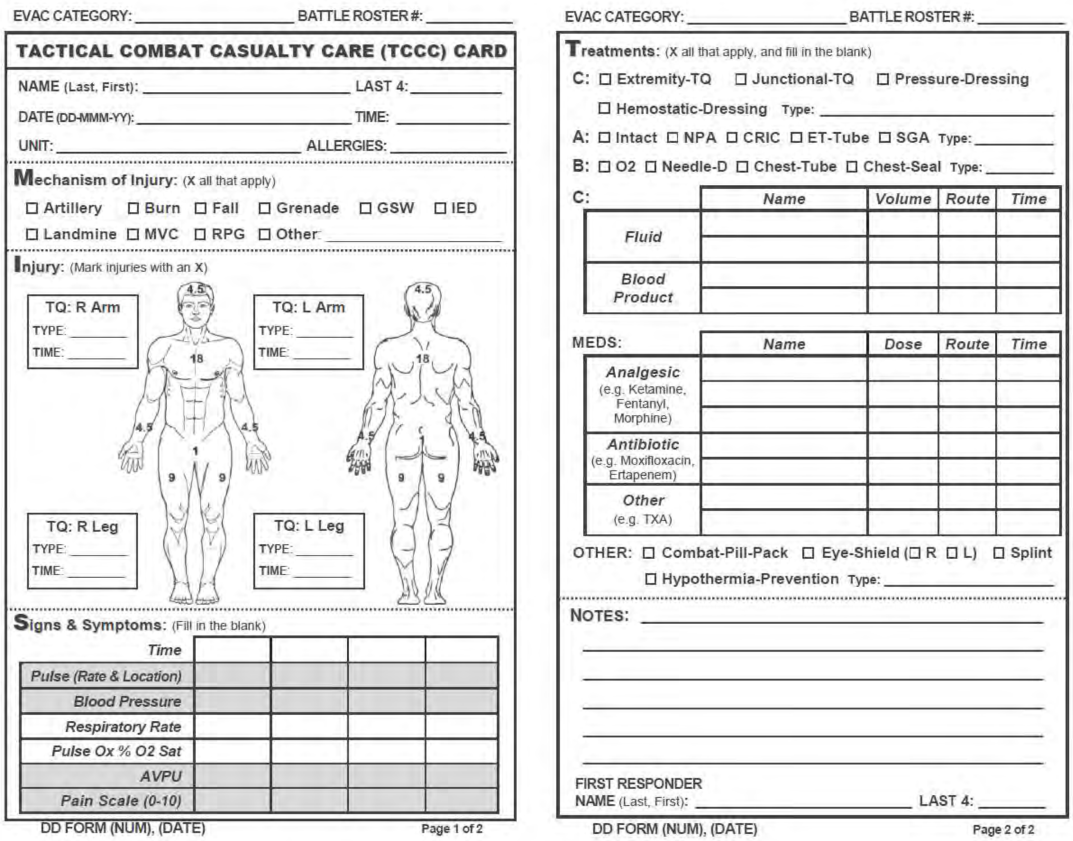
The study “We Don’t Know What We Don’t Know: Prehospital Data in Combat Casualty Care” documents the extent of the missing prehospital data problem. Researchers discovered that from October 2001 to July 2010, over 22,800 U.S. casualties were classified as having battle injuries requiring evacuation to a treatment facility (Eastridge, Mabry, Blackbourne, & Butler, 2011). Of the medical data collected from these individuals, the most common missing information was the prehospital data collected at the site of injury and transport to a military treatment facility (MTF). The missing data were attributed to the medics’ having to record vital sign data manually with pen and paper. A possible reason manual recording of vital signs is so troublesome could be what Helmus and Glenn (2005) describe as a combat zone where high stress, physical exhaustion, and operational tempo are a daily occurrence, thus medical administration can have a lower priority than physical care. However, when a soldier arrives at a treatment facility, the lack of prehospital data has been proven to place limits on the

therapeutic interventions admitting physicians can perform, thereby reducing favorable patient outcomes (Laudermilch, Nathens, & Rosengart, 2010). When reviewing the JTTS in 2011, COL Blackbourne (2011) discovered that “less than 10% of entered patients had any prehospital data, and that less than 1% had actionable information (vital signs) documented” (p. 8). This lack of data meant receiving providers had to establish baseline metrics of patients even though in most cases medics in the field already had baseline information. Additionally, communications in operating environments are limited to voice radios. These radios, while providing verbal communication to medics and MTFs, are limited in capacity. Scannel-Desh and Doherty (2010) quote an Army nurse, who said:

> My patient was a Marine sergeant. He was my first Iraq casualty. We got a radio call that they were bringing a “tourniquet injury,” which means his limbs were blown off…His corpsman had tourniqueted his extremities, and he was dark gray. He lost a lot of blood, but was still conscious and talking. He leaned up close to me and said, “Ma’am, please tell my mother and my sister ‘I’m sorry.’” Then the doc said, “Ok, we’re taking the tourniquets down now,” and within about 7 seconds he was gone. (p. 8)

While dramatic, this story provides a picture of how providers’ limited information can affect care for patients in the battlefield. Although having the vital signs data monitored by the receiving staff may not have saved the soldier, access to the sergeant’s vital signs may have assisted the provider in determining whether to remove those tourniquets at that time.

COL Blackbourne (2011) notes that further compounding the problem, medics are required to use the tactical combat casualty care (TCCC) card, a paper card issued to service members and the current preferred method for recording prehospital data (see Figure 3).



EVAC CATEGORY: ____ BATTLE ROSTER #: ____

TACTICAL COMBAT CASUALTY CARE (TCCC) CARD

NAME (Last, First): ____ LAST 4: ____

DATE (DD-MMM-YY): ____ TIME: ____

UNIT: ____ ALLERGIES: ____

Mechanism of Injury: (X all that apply)

☐ Artillery ☐ Burn ☐ Fall ☐ Grenade ☐ GSW ☐ IED

☐ Landmine ☐ MVC ☐ RPG ☐ Other: ____

Injury: (Mark injuries with an X)

TQ: R Arm TYPE: ____ TIME: ____

TQ: L Arm TYPE: ____ TIME: ____

TQ: R Leg TYPE: ____ TIME: ____

TQ: L Leg TYPE: ____ TIME: ____

4.5 18 4.5 4.5 1 9 9 4.5 18 4.5 4.5 9 9

Signs & Symptoms: (Fill in the blank)

Time				
Pulse (Rate & Location)				
Blood Pressure				
Respiratory Rate				
Pulse Ox % O2 Sat				
AVPU				
Pain Scale (0-10)				

DD FORM (NUM), (DATE) Page 1 of 2

EVAC CATEGORY: ____ BATTLE ROSTER #: ____

Treatments: (X all that apply, and fill in the blank)

C: ☐ Extremity-TQ ☐ Junctional-TQ ☐ Pressure-Dressing

☐ Hemostatic-Dressing Type: ____

A: ☐ Intact ☐ NPA ☐ CRIC ☐ ET-Tube ☐ SGA Type: ____

B: ☐ O2 ☐ Needle-D ☐ Chest-Tube ☐ Chest-Seal Type: ____

C:	Name	Volume	Route	Time
Fluid				
Blood Product				

MEDS:	Name	Dose	Route	Time
Analgesic (e.g. Ketamine, Fentanyl, Morphine)				
Antibiotic (e.g. Moxifloxacin, Ertapenem)				
Other (e.g. TXA)				

OTHER: ☐ Combat-Pill-Pack ☐ Eye-Shield (☐ R ☐ L) ☐ Splint

☐ Hypothermia-Prevention Type: ____

NOTES: ____

FIRST RESPONDER NAME (Last, First): ____ LAST 4: ____

DD FORM (NUM), (DATE) Page 2 of 2

Figure 3. Example of paper documentation issued to military members for recording vital sign and other medical data (from Summers, 2013).

Although an improvement over previous options, using the TCCC cards still requires medics to manually transcribe vital signs data, a method which is subject to poor documentation, errors in transcription, illegible handwriting, and possible loss of the TCCC card during patient transit. Leveraging technological advancements to allow for remote monitoring of wounded soldiers and an automatic documentation platform would eliminate the need for TCCC cards and enable vital sign data to flow to a receiving treatment facility automatically. By allowing real-time monitoring of patient vital signs, medical doctors could track casualties during transport and offer support to attending medics.

D. THE BASICS: UNDERSTANDING THE VITAL SIGNS

To address the problem of monitoring and documenting vital signs with sensors, we needed to identify the technical requirements necessary for vital sign capture and recording. To do this, we had to define the term *vital signs* and understand the measurement of each. According to the National Institute of Health, vital signs are measurements of the body's most basic functions. The three main vital signs routinely monitored by medical professionals and healthcare providers include body temperature, pulse rate, and respiration rate (National Institute of Health [NIH], 2015). Blood pressure is not considered a vital sign but generally is taken with the vital signs (Johns Hopkins University of Medicine, 2015). Following the practice of John Hopkins Medicine, we are omitting blood pressure monitoring as a sensor requirement and focusing on pulse, respiration, and temperature as metrics. Vital signs are usually assessed using a stethoscope, thermometer, and blood pressure cuff. Traditionally these have been manual devices, but recently there has been a move to automated vital signs machines, which can be used bedside or remotely with a battery (see Figure 4).

Figure 4. Examples of automatic and standard vital sign instruments (from http://www.apkmodgame.net/tag/vital-sign-machine).

1. Body Temperature

According to the Johns Hopkins University of Medicine (2015), the normal body temperature of a person varies depending on gender, recent activity, food and fluid consumption, the time of day, and, in women, the stage of the menstrual cycle. Normal body temperature can range from 97.8 to 99.1 degrees F for a healthy adult. A person's body temperature can be taken orally, rectally, axillary (under the armpit), by ear, or by

the skin; the latter measuring option is of most interest to our sensor research. In many cases, the temperature is the most important vital sign as it is one of the first clues the body is fighting off an infection (John Hopkins Medicine, 2015).

2. Pulse Rate

The pulse rate is a measurement of the heart rate or the number of times the heart beats per minute. As the heart pushes blood through the arteries, the arteries expand and contract with the flow of the blood. The normal pulse rate for healthy adults ranges from 60 to 100 beats per minute (John Hopkins Medicine, 2015). Taking a pulse indicates the heart rhythm and strength of pulse, and knowing these factors can assist in identifying shock or congestive heart failure (NIH, 2015).

3. Respiration Rate

The respiration rate is the number of breaths a person takes per minute. The rate is usually measured when a person is at rest and simply involves determining the number of breaths for one minute by counting how many times the chest rises. Respiration rates may increase with fever, illness, and other medical conditions. Normal respiration rates for an adult at rest range from 15 to 20 breaths per minute. For further clarity, consider Table 1.

Vital	Definition	Measurement	Normal
Pulse Rate	Indicates the heart rhythm and strength of pulse	The number of times the heart beats per minute	60 to 100 beats per minute
Respiration Rate	The number of breaths a person takes per minute	Visual counting of chest rises	15 to 20 breaths per minute
Temperature	Measures the core body temperature	Orally, rectally, axillary (under the armpit), by ear, or by skin	97.8 to 99.1 degrees F

Table 1. Vital sign measurements (after NIH, 2015).

E. SENSORS

The term *wireless sensor network* (WSN) denotes wireless communication, sensor design, and energy storage technology for monitoring (Yang, 2006). This term refers to the integration of microsensors no more than a millimeter in size with onboard processing and wireless data transfer capability. The evolution of the microsensors can be traced to the microelectromechanical systems (MEMS) "smart dust" concept, which sought to put self-contained ultralow power nodes into the battle space to monitor movement (Kahn, Katz, & Pister, 1999). Since 1998, advances and application of microsensors have continued to move forward at a steady pace. Consider Figure 5, which displays the physical changes of sensors since 1998.

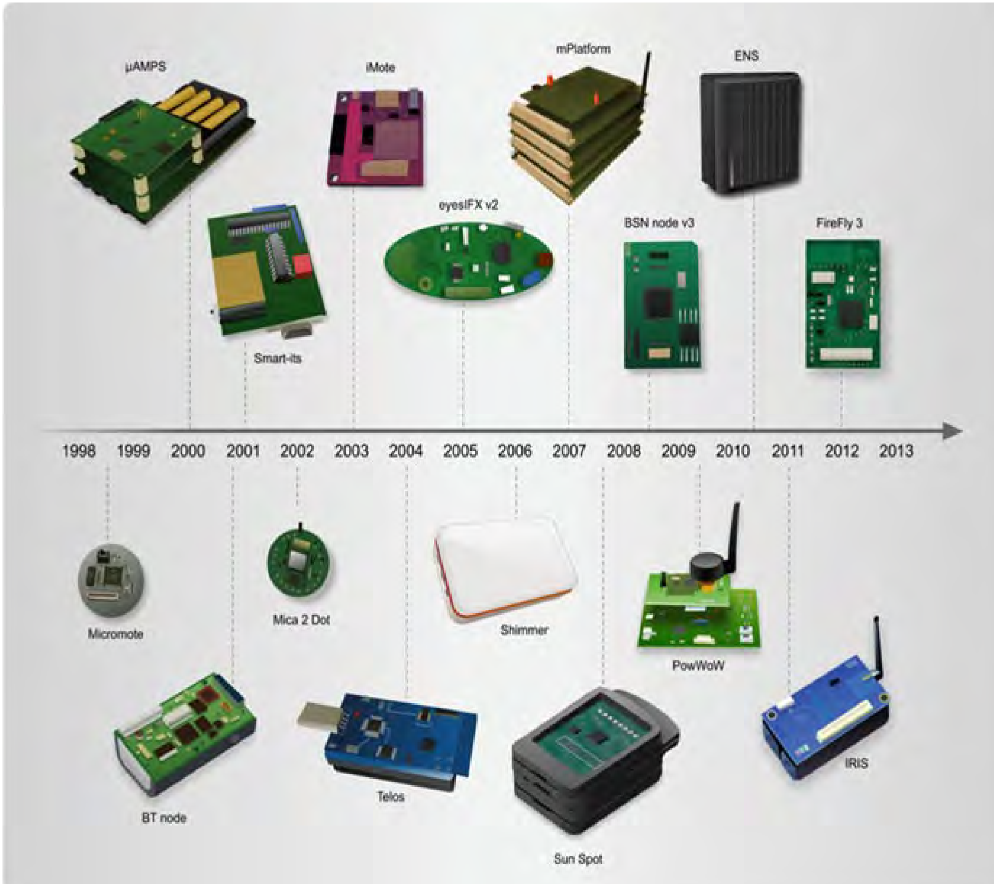


Figure 5. Evolution of biosensors (from Yang, 2006).

According to Yang (2006), WSNs can be categorized into three types of sensors: indoor, outdoor, or urban. These three types of sensors are beginning to impact many everyday processes in both industry and private life. The term *Internet of things* (IoT) describes the coming new era of the networked interconnection of everyday objects, which will fundamentally change communication options. "IoT will increase the ubiquity of the Internet by integrating every object for interaction via embedded systems, which leads to highly distributed network devices communicating with human begins as well as other devices" (Xia, Yang, Wang, & Vinel, 2012). "Smart houses" are already utilizing radio-frequency identification (RFID) technologies in multistandard NFC and ultrahigh frequency (UHF) architectures to communicate tasks such as remotely turning lights on or increasing the heat before the homeowners arrive home (Darianian & Michael, 2008). However, while WSNs are having an impact on a broad range of applications, the

challenges of monitoring and recording the body remain. Yang (2006) claims that the human body is a challenge because it consists of a complicated internal environment that responds to and interacts with its external surroundings. *Body sensor network* (BSN) and *wireless body area network* (WBAN) are interchangeable terms most professionals utilize when addressing the human network (Niemela et al., 2014).

F. BSN AND WBAN NETWORKS

Both BSN and WBAN are network configurations that utilize sensor technology to monitor and record biometric information. Niemela et al. (2014) describe both networks as numerous sensors placed on or in a human body for performing ongoing measurements of body vitals, possibly even processing the data, and transferring the data to a server accessed by necessary persons, including the patient, and nursing personnel. Monitoring platforms have adopted numerous strategies to deploy sensors, including having them worn via straps, integrated into clothing, or even implanted within the body (Yang, 2006). Consider figure 6.

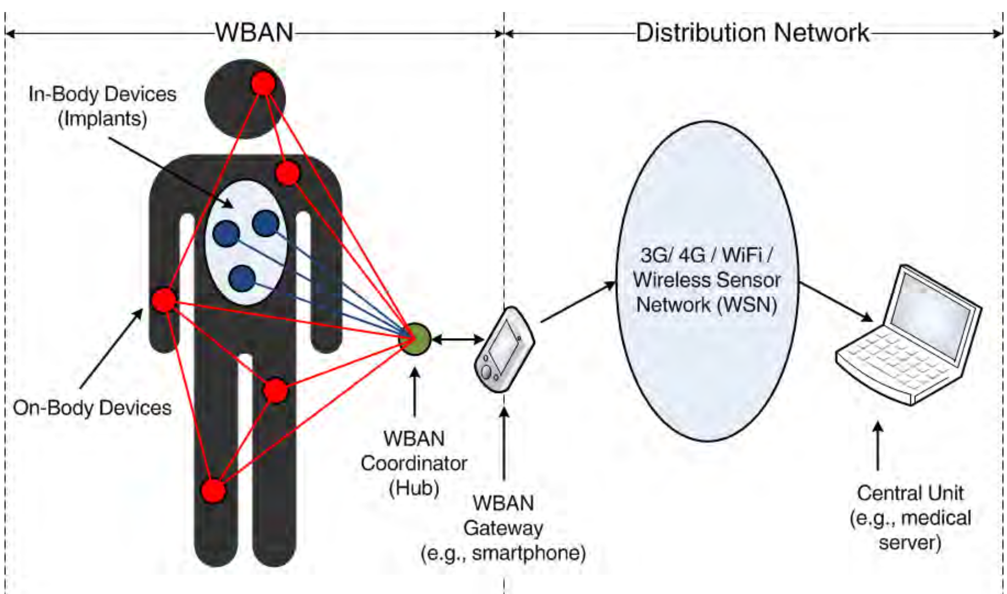


Figure 6. Sensors within WBAN networks (from Kartsakli et. al., 2013).

G. COMMUNICATION PLATFORMS

According to IEEE (2011), BSNs operate in compliance with the IEEE 802.15 standard. This standard includes multiple protocol standards such as 802.15.1 (Bluetooth), 802.15.3 (high rate wireless personal area network (WPAN)), 802.15.4 (low-rate WPAN), 802.15.6 (WBAN). The ZigBee standard expands upon IEEE 802.15.4. The protocol requires compatible interconnection for data communication devices using low-data-rate, low-power, and low-complexity short-range radio frequency (RF) transmissions in a WPAN. ZigBee's standard specifies the physical layer and media access control for low-rate WPANs. IEEE 802.15.4 includes real-time suitability by reservation of guaranteed time slots, collision avoidance through carrier sense multiple access with collision avoidance (CSMA/CA), and integrated support for secure communications (IEEE, 2011).

H. SENSOR STUDIES IN VITAL SIGNS

The use of wireless sensors to capture vital signs is an emerging field throughout medicine. An important requirement of sensor adaption is the accuracy of vital sign capture vice the traditional manual method. Any lack of confidence in the measurement of vital sign data by providers would limit the adoption of this technology. To determine if a distinction between vital sign data capture was evident between wireless sensor and manual measurement processes, Kiokes et al. (2014) conducted a study to test the ability to monitor and track athletes' vital signs in a WSN. The result of the study revealed that mobile values acquired wirelessly were generally equal to those acquired in fixed environments (Kiokes et al., 2014). In their study, Kiokes et al. (2014) used the Arduino Uno monitoring system and placed wireless sensor nodes on four athletes to measure their vital signs during training. During conditioning, each sensor would wirelessly transmit data to the coaches' terminal using a star topology. The Arduino Uno operated on the ZigBee application framework and communicated wirelessly to the coaches' terminal as the four athletes moved around the stadium. Researchers found a positive correlation when utilizing wireless sensors for the transmission and recording of vital signs and recommended further analysis for inclusion in mesh networks.

Another study focused on the need for wireless vital signs monitoring during urban search and rescue (USAR) operations (Pallis, Ferreria, Hildebrand, & Seynaeve, 2014). Utilizing the Zephyr BioHarness 3, a team of researchers studied the applicability of wireless vital sign monitoring for victims trapped in collapsed buildings. The findings were mixed. While the Zephyr allowed for the transmission of vital sign data, complications with the device proved difficult to overcome. The device required a chest strap to be worn, which in most cases was impossible to use on the trapped victims. Thus, when first responders tried to utilize the sensors, they found it difficult, if not impossible, to wrap the sensors around the trapped patients' bodies.

In their study of wireless sensors in medicine, Hernandez-Silveira, Ang, and Burdett (2014) utilized the Sensium digital patch in an effort to overcome the bulky bedside monitors and static process of wires attached to patients. The wireless, unobtrusive, lightweight, and disposable body-worn device was designed to monitor vital signs (temperature, heart rate, and respiration rate) in real time. The findings were mixed. While the digital patch freed up a patient to move around, allowing providers to monitor and record vital sign data wirelessly, the patients' physical motion of walking created errors in the data. The errors from the sensor data called into the question the accuracy of the vital sign data, which resulted in staff having to re-administer vital signs to confirm accuracy (Hernandez-Silveira et al., 2014).

I. SENSOR DESIGN AND INTEGRATION CHALLENGES

Although most articles we reviewed regarded BSNs as the future for monitoring vital signs, most agreed on the basic challenges which still need to be addressed. These challenges include sensor design, integration, power-source miniaturization, and reliability.

1. Sensor Design

With the rapid growth of the use of smart phones, size and functionality are common requirements for users. This is also true with sensors. In the article "Nanowire Biosensors," Nair and Alam (2007) conclude that despite the tremendous potential of biosensors, careful optimization in design is a key factor in ensuring optimal sensor

performance. For implementation within the military, the design must be small enough to not impede the service member.

2. Integration

Another important challenge sensors must overcome is integration with other systems. Standardization of sensors in other areas in medicine has been shown to provide better outcomes. This is evident with the recent cardiac pacing technologies, which, according to Trohman, Kim, and Pinski (2004), expanded substantially due to standardization. For sensor adaption to gain a wider acceptance, proprietary equipment must be phased out.

3. Power-Source Miniaturization

According to Yang (2006), power consumption determines not only the size of the battery required but also the length of time sensors can be used. Therefore, future designs must minimize power consumption. Sensors utilizing ZigBee or ultra wideband radio are suggested as the solution to this problem (Porcino & Hirt, 2003). Porcino and Hirt (2003) recommend sensors that utilize ZigBee or ultra wideband radio, pointing out that short-range wireless technology is the key component of the IoT trend, where "everyone and everything" is connected.

4. Reliability

As Hernandez-Silveira et al. (2014) discussed earlier, medical information transmitted utilizing sensors must be accurate if it is going to be adopted by medical providers. Studies have shown that any disruptive technology in an organization must overcome the human element. People, as creatures of habit, have a hard time transitioning to different processes even if the new process is better. Kulkarni and Ozturk (2010) discuss this problem in a study examining sensor system adaption in healthcare and note that cultural and socioeconomic factors play a key role in determining the speed at which sensors are adopted within healthcare. Thus, for wireless sensors to be adopted by users, the data being monitored and transmitted must be accurate.

When analyzing the literature for vital sign sensors, our goal was to determine what constitutes a vital sign and if capabilities exist to wirelessly automate this process. We found a prevalent theme in literature: the need to discover a wireless automatic solution to remedy deficiencies in historical monitoring and recording methods. Case studies in sensor adoption have attempted to implement biosensors in different environments with mixed results. When reviewing the engineering requirements of a vital sign monitoring sensor, we discovered the three prominent challenges for the design of the sensor: integration, power-source miniaturization, and reliability.

III. INTEGRATING VITAL SIGNS SENSORS INTO WIRELESS NETWORKS

Wireless sensor networks come in many forms and levels of complexity. This diversification is needed because of the variety of uses for sensors. This chapter discusses the typical physical topology and protocol standards used in vital sign transmission in WSNs.

A. TOPOLOGY

Network topology can be defined utilizing the International Organization for Standardization (IOS) Open Systems Interconnection (OSI) seven layer model. This model was developed to provide partitioning of each layer as an abstraction layer, increasing interoperability but maintaining individuality. “Layering divides the total problem into smaller pieces…ensuring independence of each layer by defining services provided by a layer to the next higher layer, independent of how these services are performed” (Zimmerman, 1980, p. 426). The first two layers (physical and link layers) of the OSI model define the physical and logical topology of a wireless network. Figure 7 identifies common physical network topologies utilized in WSNs and discusses the advantage and disadvantages of each.

Topology	Advantages	Disadvantages
Star	Simplicity Simple and cheap slave nodes Low power consumption of slave nodes Low latency and high bandwidth Centralised systems	Dedicated central node Limited spatial coverage Single point of failure Poor scalability, small number of nodes Asymmetric power consumption (master consumes much more energy than slaves) Inefficient slave-to-slave communication Distributed processing
Mesh	Distributed processing Peer-to-peer communication Very fault tolerant Scalable, many nodes possible Large spatial coverage Low/medium complexity Energy consumption can be balanced among nodes	Nodes used must have same basic functionality, including routing capabilities (may be an overkill in some applications as it increases cost) Complexity of routing High latency and low bandwidth
Star-mesh hybrid	Low/medium complexity (if nodes can be classified as slaves or masters before deployment) Large spatial coverage Low latency and high bandwidth between master and its slaves Good for local actuation or data aggregation High reliability possible Scalable, many nodes possible Power consumption can be balanced among masters and it is asymmetrical between master and slaves Nodes acting as slaves can be relatively inexpensive	High complexity (if all nodes can act as masters) High latency and low bandwidth for multi-hop communication Power consumption is asymmetrical between master and slaves
Cluster tree	Low power consumption of leaf nodes Large spatial coverage area Many nodes possible Large spatial coverage Medium complexity (rerouting is required when a node in the tree dies)	Medium scalability (root of the tree is a bottleneck) Low reliability (node failure affects routing) High latency and low bandwidth Asymmetric power consumption (nodes in the tree backbone consume more power) Nodes used must have same basic functionality, including routing capabilities (may be an overkill in some applications)

Figure 7. Topology advantages and disadvantages (from Yang, 2006).

The choice of topology used for vital sign transmission is use case dependent. In a non-austere and limited mobility environment such as a hospital, the topology of choice would be a star configuration. This is due to its low cost and simple design scheme that utilizes a centralized system. A star topology would not be a feasible solution in an environment where the monitored subjects are highly mobile and network scalability (the ability to increase or decrease the number of vital sign monitored persons) is a factor. This use case would be better suited for a mesh or star mesh hybrid topology solution due to the highly scalable and large coverage area characteristics.

B. PROTOCOL STANDARDS

Similar to network topology, the choice of wireless sensor protocol standards for vital sign transmission is use case dependent. While one standard may provide better range, the disadvantage normally lies in the increase in power consumption and larger size requirement (Yuce & Ho, 2008). The following sections discuss the typical wireless sensor protocol standards used in vital sign transmission.

1. 802.15.1 Medium Rate WPAN

The IEEE 802.15.1 standard defines the implementation of medium rate WPANs, also known as Bluetooth®. This standard was developed to replace the need for cables to connect portable and fixed electronic devices (IEEE, 2005). Bluetooth utilizes 79 channels within the unlicensed 2.45 GHz industrial scientific and medical (ISM) band while operating in a master/slave configuration. The master node is responsible for clock synchronization of slave nodes and determination of frequency hopping patterns. This frequency hopping characteristic is implemented to combat RF interference and fading (IEEE, 2005). As indicated in Figure 8, the OSI layers are expanded upon to develop the Bluetooth® protocol stack.

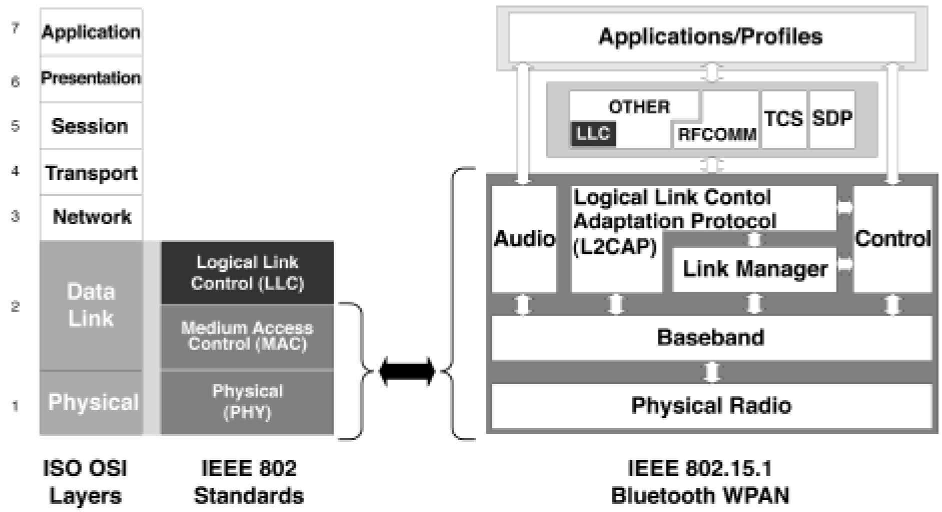


Figure 8. ISO OSI layers compared with 802.15.1 (from IEEE, 2015).

Bluetooth technology has increased in popularity among vital sign sensor vendors in recent years due to the newly developed low-energy protocol stack (Pantelopoulos & Bourbakis, 2010). The Bluetooth low-energy technology allows for consumption of only a small fraction of the power of the original Bluetooth products and is targeting sports and wellness and healthcare devices (Pantelopoulos & Bourbakis, 2010). Data rates range between 1 and 3Mbps. The disadvantage lies in the overall transmission range of 10 meters (Yuce & Ho, 2008).

2. 802.15.3 High Rate WPAN

The goal of IEEE 802.15.3 was to provide for low-complexity, low-cost, low-power-consumption and high-data-rate (20 Mb/s or more) wireless connectivity among devices within or entering the personal operating space, 10 meters, while implementing quality of service capabilities for multimedia data support (IEEE, 2009). Because of its relatively low maximum data rate, the 802.15.3 did not meet the success of other competing standards, specifically 802.11 (Yang, 2006). In 2009, an amendment to the original standard was introduced that offered an alternative physical layer operating in the 60 GHz band, which resulted in data rates of greater than 5 Gbps (Yang, 2006). This standard has been deemed not efficient for the use of wireless sensors because of the

small size of data packets required for a typical vital sign monitoring scenario (Yang, 2006).

3. 802.15.4 Low-Rate WPAN

The IEEE 802.15.4 defines the physical and medium access control layer specifications for low-data-rate wireless connectivity (IEEE, 2011). As shown in Figure 9, the physical layer is capable of using many different frequency bands.

Band (MHz)	Region	Number of channels	Modulation	Data rate (kbps)	Support
868–868.6	Europe	1	BPSK	20	Mandatory
			ASK	250	Optional
			O-QPSK	100	
779–787	China	8	MPSK	250	Mandatory
			P-QPSK		
902–928	USA	10	BPSK	40	Mandatory
			ASK	250	Optional
			O-QPSK	100	
950–956	Japan	22	BSPK	20	Mandatory
			GFSK	100	
2,400–2,483.5	Worldwide	16	O-QPSK (DSSS)	250	Mandatory
		14	CSS		Optional
			CSS	1,000	
249.6–749.6 (UWB sub-gigahertz)		1	BPM and BPSK	110–27,400 (varying w.r.t. chip rate)	Optional
3,244–4,724 (UWB low band)	Worldwide	4	BPM and BPSK	110–27,400 (varying w.r.t. chip rate)	Optional
5,944–10,234 (UWB high band)		11	BPM and BPSK	110–27,400 (varying w.r.t. chip rate)	Optional

Figure 9. The physical specifications supported by IEEE 802.15.4 (from Yang, 2006).

The physical layer also dictates the activation and deactivation of the transceiver, energy detection, link quality indicator, channel selection, clear channel assessment (CCA), and transmitting and receiving (IEEE, 2011). As defined by IEEE, the Media

Access Control (MAC) sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC sublayer management entity. The main features of the MAC sublayer are beacon management, frame validation/acknowledgment, and control access to the physical layer through the use of CSMA/CA.

The 802.15.4 standard can be used to create a star or peer-to-peer network. To reduce the cost of this implementation, devices were divided into full-function device (FFD) and reduced-function device (RFD) categories. The FFD has the ability to act as the personal area network (PAN) coordinator. The PAN coordinator’s role is to control the association of nodes as well as initiating, terminating, and routing communication (Yang, 2006). Figure 10 provides examples of the utilization of the PAN coordinator within both topologies.

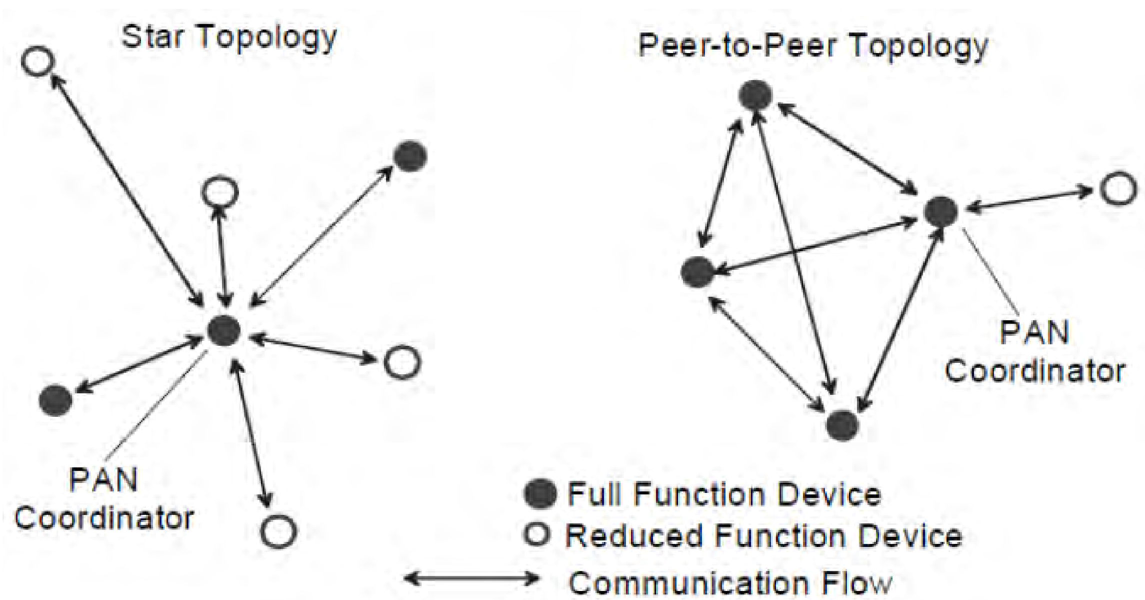


Figure 10. PAN coordinator placement in topology (from IEEE, 2011).

a. ZigBee

The ZigBee Alliance expanded upon the 802.15.4 to include a network and application layer that provides a framework that vendors can utilize to ensure compatibility of products. Figure 11 shows the ZigBee architecture and its relation to the 802.15.4 standard.

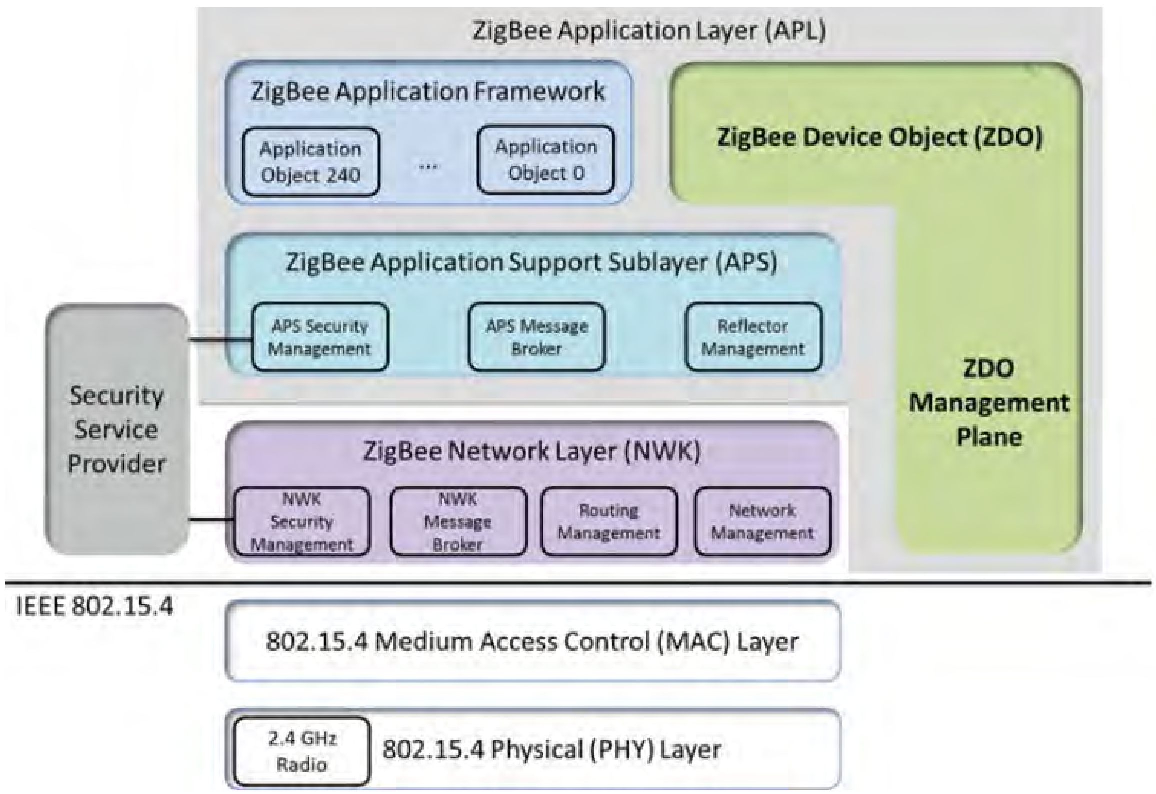


Figure 11. ZigBee architecture in relation to the IEEE 802.15.2 standard (from Yang, 2006).

ZigBee utilizes three types of devices: ZigBee coordinator, ZigBee router, and ZigBee end device. These three mirror in behavior the 802.15.4 defined devices PAN coordinator, FFD, and RFD respectively. Their typical range is anywhere from 10 to75 meters (Pantelopoulos & Bourbakis, 2010).

One aspect of particular interest in the implementation of ZigBee is the Alliance's development of application profiles. These application profiles provide a device

description, cluster (data entities), and service types. The profiles are developed with the consensus of vendors who take part in the Alliance. The current list of application profiles spans 10 categories including healthcare. The healthcare profile is segmented into three concentration areas (personal wellness, health and fitness, and disease management), which are defined in Figure 12. These three concentration areas provide the basis for interoperability in that products from other vendors can call upon and communicate between devices by standardizing the data format.

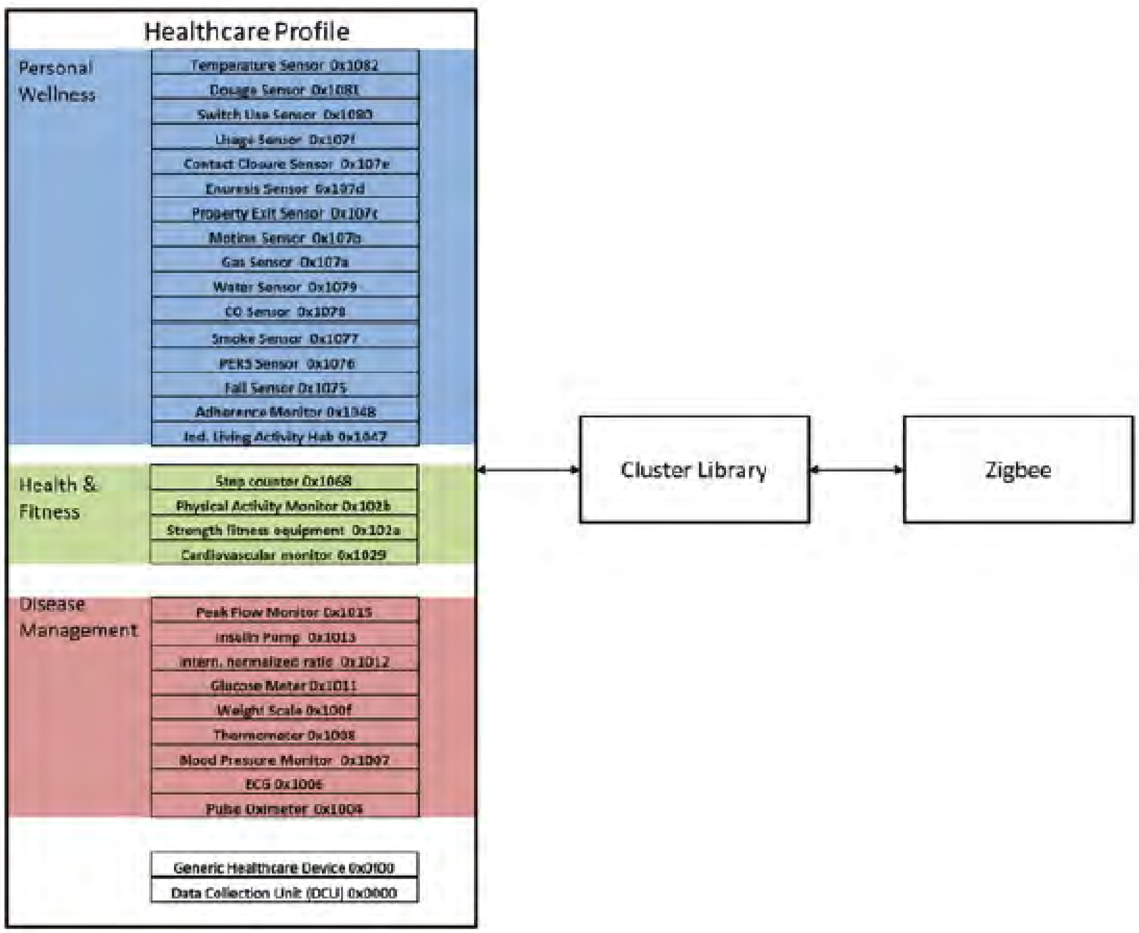


Figure 12. Three concentration areas of the healthcare profile sensor application (from Yang, 2006).

Due to ZigBee's utilizing the same frequency as wireless local area networks, 2.4 GHz, coexistence can be challenging (Yuce & Ho, 2008). Data rates may also be an issue due to the relatively small throughput of approximately 250Kbps (Pantelopoulos & Bourbakis, 2010).

4. 802.15.6 Wireless Body Area Networks

The 802.15.6 standard was developed to enable short-range (2 meters) communications inside, on, or around the human body (Yang, 2006). The chart in Figure 13 identifies some of the use cases for this standard.

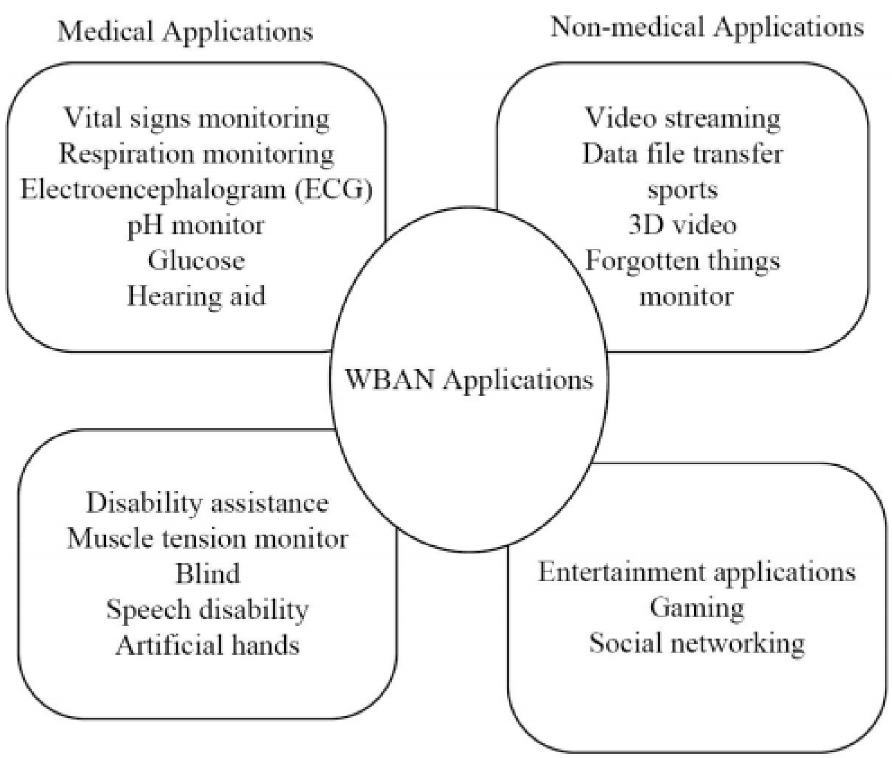


Figure 13. WBAN use cases (from IEEE, 2012).

WBAN uses the ISM bands as well as frequency bands approved by national medical or regulatory authorities (IEEE, 2012). IEEE addresses the physical layer, MAC layer, data encryption, and authentication within this standard. The physical layer is divided into narrowband, ultra wideband, and human body communication categories.

Narrowband is considered optimal for medical applications, both for wearable and implanted networks, by providing a scalable data range between 100 and 1,000 Kbps (Yang, 2006). Ultra wideband provides more robust capability that includes high-reliability, low-complexity, and ultralow-power operation (Yang, 2006). Human body communication utilizes the body as the transmission medium instead of a physical antenna; it operates at 21 MHz.

IV. INTEGRATION OBSERVATIONS

The observations in this chapter were performed during lab testing in preparation for an experiment aboard the USCG ship *ADM. Callaghan*. The intended purpose of the experiment was to conduct integration testing of a COTS wireless vital sign monitoring sensor with a mesh infrastructure. Yet, because of proprietary hardware and fiscal and time constraints, the experiment aboard USCG *ADM. Callaghan* was not performed. This chapter details the observations found within the lab environment.

A. COMMUNICATION EQUIPMENT

For this experiment, communication equipment from two COTS vendors was selected: TrellisWare radios and Zephyr wireless vital sign monitoring sensor BioHarness 3. The TrellisWare tactical radios were chosen based on previous research performed by the Naval Postgraduate School Center for Network Innovation and Experimentation (CENETIX) laboratory. In a 2014 study, Aras found that due to their relatively low frequency and hull penetration ability, TW-230 radios provided adequate voice communication utilizing only four nodes onboard USCG ship *ADM. Callaghan* (Aras, 2014). The Zephyr BioHarness 3 was chosen due to previous successful implementation of Zephry products within tactical operational environment.

1. TrellisWare TW230 Radios

The TW230 radio is part of the Tactical Mobile Ad-Hoc Network family of radios developed by TrellisWare. Since this is an OSI Layer 3 device, scalability is not an issue. TW230s automatically establish mesh network connections when a new device is introduced to the network. A photo of the radio and specifications are provided in Figure 14 and Table 2.

Figure 14. TW230 radios (from TrellisWare, 2012).

Features	Specifications
Transmit Power	2 Watt Peak (selectable 100 mW, 250 mW, 500 mW, 1 W, and 2 W)
Frequency Ranges	30 - 225 MHz, 225 - 512 MHZ, 1755 - 1815 MHz (3 segments); 2200 - 2270 MHz (4 segments)
Relay Support[1]	Up to 8 hops for voice and data
Position Location[1]	Integrated GPS with stub antenna or powered patch antenna
Security[1]	AES-256 keys for each voice and data channel
Size (w/o accessories)	4.75" (H) x 2.63" (W) x 1.50" (D)
Weight	32 oz (R/T unit), 2 oz (sensor dongle)
Maximum Data Rate[1]	2.5 Mbps IP data rate @ 8 hops
Host Interfaces	Ethernet, Analog Video, Trigger In / Out
External Connectors	24-pin multifunction, 6-pin audio, TNC antenna, SMA GPS antennas
Environmental Compliance	Meets MIL-STD-810F with 2 meter immersion (R/T)
Input Power	6-18 Volts DC
Radio Configuration	Frequencies / crypto / network parameters / sensor settings from web application
Operator Controls	Volume on/off with zeroize, channel select, push button display menu controls
Data Types[1]	AMR 5.9 voice, IPv4 or IPv6 data, streaming video/audio
Video / Audio Encoding[1]	MJPEG with AMR for audio over voice channel
Audio Channels[1]	Up to 8 channels
Headsets	Peltor Comtac, Nacre QuietPro, Silynx, H-250, Clear Tone and settings for additional types
Audio Latency[1]	3 Hop < 250 ms; 8 Hop < 400 ms
Net Entry Time [1]	< 1 sec
Antenna	Support TNC connector non-power antennas for each freq band
Battery Run Time	1+ week continuous, 30+ days WoW, 10+ months WoT (on MBITR battery)
Occupied Bandwidth	4 to 20 MHz (TSM), 12.5 or 25 KHz (FM), 25 KHz (AM)
IP Support [1]	Full IP supports Unicast, Multicast, Broadcast and full TCP support
Power Conservation [1]	Wake-on-Wireless / Wake-on-Trigger / Active

[1] TSM Mode Only

Table 2. TW230 specifications (from TrellisWare, 2012).

2. Zephyr BioHarness 3 Sensor

The BioHarness 3 is a physiological monitoring module that, when paired with a chest strap, can incorporate electrocardiogram (ECG) and breathing detection sensors. The BioHarness 3 is worn against the skin by the participant via an elasticated strap attached around the chest (see Figure 15). The BioModule acts as a transmitter and has a memory of up to 500 logging hours with an expected battery life of up to 30 hours. Five

variables are measured simultaneously, time stamped, and exportable to a .csv format. Heart rate data are captured through electrode sensors housed within the chest strap sampled at 250 Hz and reported as beats per minute. Breathing is measured by a capacitive pressure sensor that detects circumference expansion and contraction of the torso as an output as breaths per minute. Temperature data are collected through an infrared sensitive sensor behind a clear window on the apex of the monitoring device. It records peripheral skin temperature at the inferior sternum. This sensor reports data in degrees Celsius (°C). A position and posture sensor is used to determine if a participant is lying down or standing. The ability to differentiate between a lying and standing position is significant when monitoring vital signs because the physical posture of the human body is known to provide different results (Witting & Gallagher, 2003). Lastly, the three-axis accelerometer provides measurement of up to a force of 16g. A picture of the device, features, and RF characteristics are provided in Figures 15 and 16 and Table 3, respectively.

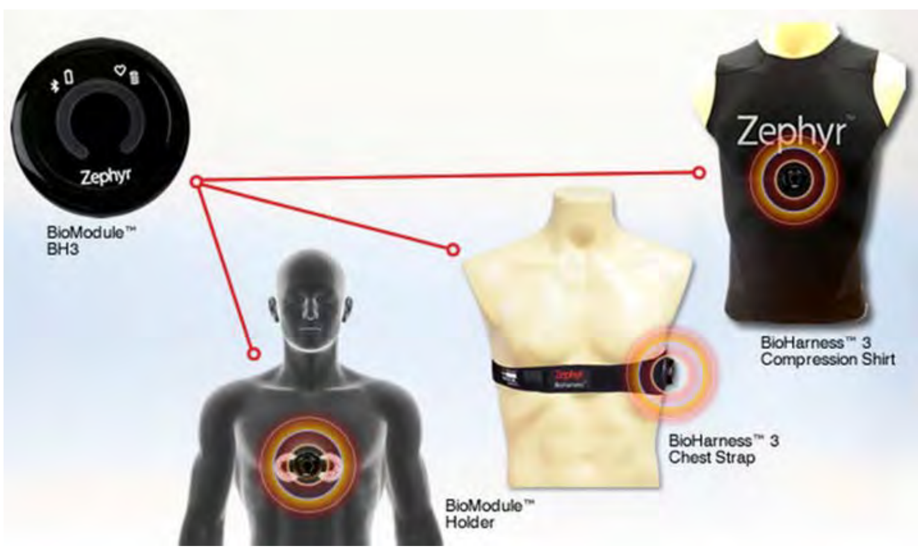


Figure 15. BioHarness 3 with chest strap or compression shirt (from Zephyr, 2014).

- Bluetooth Connectivity to receiver or external sensors
- IEEE 802.15.4 Connectivity
- Heart Rate 0 – 240 BPM (±1 BPM)
- Breathing Rate 0 – 120 BPM (±1BPM)
- Device Temperature 10 – 60°C (±2°C)
- Position/posture ± 180° (Laying, standing)
- Activity in VMU (Stationary, walk, run)
- 3 axis Acceleration to 16g
- Red / Orange / Green subject status indication
- Transmit and/or Logging Modes
- 250Hz ECG Transmission & Logging
- 100Hz Accelerometer Logging
- USB connectivity for data download & charging
- Up to 500+ hours data storage
- Internal algorithms for
  - Estimated core temperature
  - Jump Test
  - Dash Test
  - Heart Rate Variability
  - Human Real Data

Figure 16. BioHarness 3 composite capabilities (from Zephyr, 2014).

Bluetooth	
Bluetooth Compliance	Version 2.1 + EDR
Supported Profile	Serial Port
Discoverability	Configurable
Frequency	2.4 to 2.835 GHz
Output Power	10 dBm
Operating Range	Up to 300ft / 100m. Up to 300yds with long range receiver antenna (Dependent on Bluetooth receiver components)
Sensitivity	-91 dBm
Antenna Type	Internal

802.15.4 (ECHO Network)	
Compliance	IEEE 802.15.4
Frequency	2.405 – 2.480 GHz
Output Power	100mW
Operating Range	Up to 300 yards / 275 m
Sensitivity	-89 dBm
Max Data Rate	250 kbps
Modulation Type	OQPSK
Spread Spectrum	DSSS

Table 3. BioHarness 3 RF characteristics (from Zephyr, 2014).

B. INFRASTRUCTURE DESIGN

The lab test scenario was to incorporate multiple BioHarness 3 sensors. Each sensor would be paired to a single TW-230 radio interface device utilizing Bluetooth technology to connect to the mesh topology. We chose Bluetooth as the preferred RF transmission medium because it was the common protocol between the two devices. The TW-230 radios would be preconfigured in a mesh network with one of the TW-230 utilized as an end node. This end node would transmit all of the networked sensor data to the remote server for storage and viewing. A healthcare provider could then utilize the monitoring client to view real-time vital sign data using standard Internet protocols.

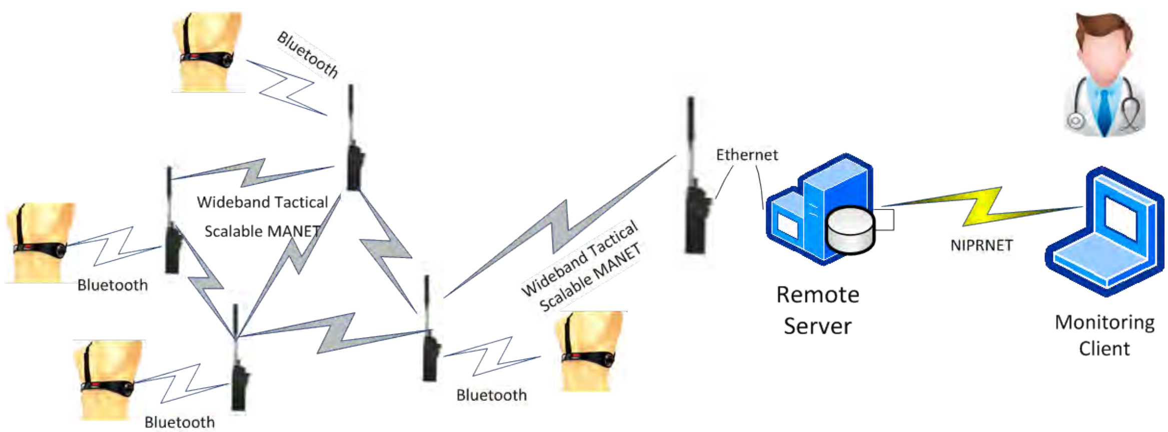


Figure 17. Lab test infrastructure design.

For the TW-230s to communicate via Bluetooth, a separate radio interface device (RID) is required. The RID plugs directly into the side of the radio and requires software version 4a Beta5 or higher. Figure 15 shows a picture of the RID.

Figure 18. TW-230 Bluetooth radio interface device (from TrellisWare, 2012).

C. CONNECTIVITY OBSERVATION

Problems soon arose during the initial pairing of the TW-230 radio and the BioHarness 3. We found that both the TW-230 and BioHarness 3 were not able to operate in a Bluetooth master mode, which is required in a master/slave relationship. While connections were established directly to a Bluetooth-enabled laptop by both devices, connections could not be established between the TW-230 and BioHarness 3. Further investigation led to a proposed solution by Zephyr that entails the purchase of their proprietary RID. This was not pursued due to time constraints.

D. CONNECTIVITY VIA GATEWAY

We shifted the lab test focus from integration of the BioHarness 3 into the mesh network to an observation of the sensor utilizing the Zephyr Echo Gateway that came with the product. The Echo Gateway can be seen in Figure 19 connected on the right side of the laptop. The gateway uses 802.15.4 technology and allows the remote computer to view live data from multiple sensors using the accompanying software.

Figure 19. Zephyr BioHarness 3 module (left), chest strap (center) and gateway (right).

Connectivity between the BioHarness 3 module and the gateway was established without issue once the accompanying software configuration was changed from “Bluetooth” to “Echo” network within the general setting of the preference menu. After donning the chest strap, the subject’s ECG and breath rate data was only captured after dampening two areas on the chest strap as recommended in the manual. The range was typical of a device operating in this frequency and power combination.

E. SOFTWARE OBSERVATIONS

The Zephyr BioHarness 3 was shipped with two different software applications, OmniSense and OmniSense Analysis. OmniSense, the live data monitoring software, can be viewed in Figure 20.

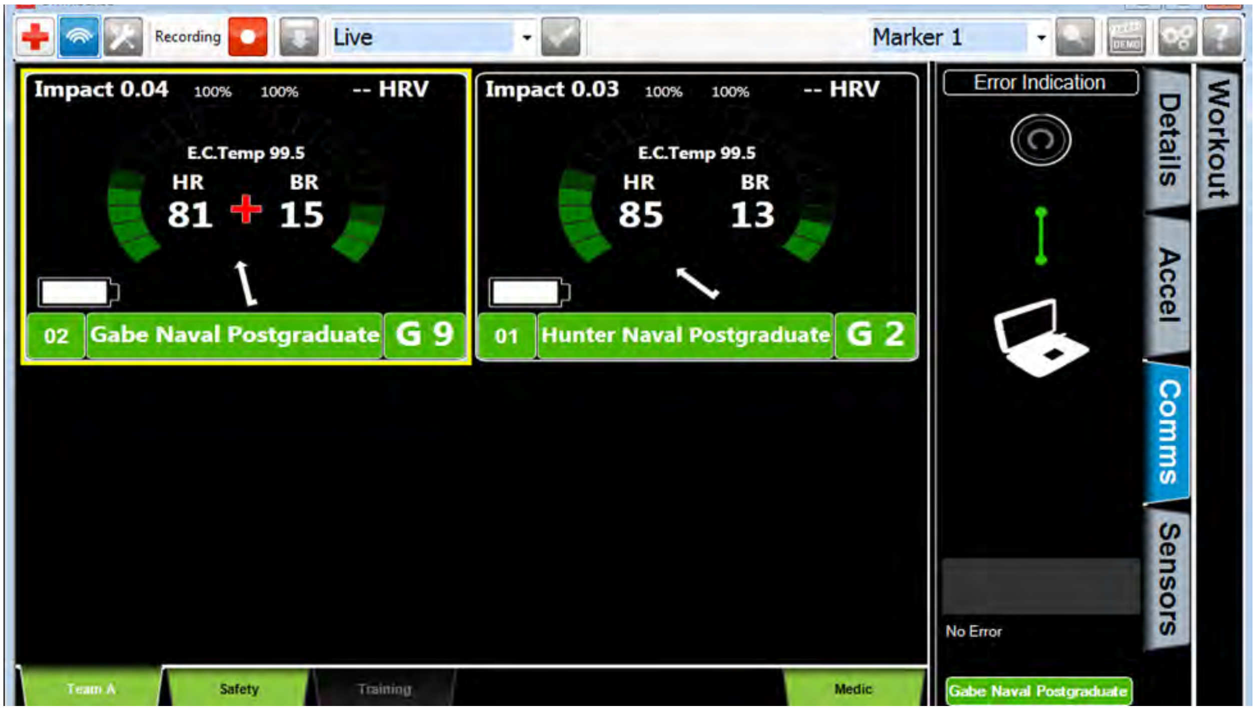


Figure 20. Zephyr OmniSense live monitoring application display.

OmniSense is a highly customizable application that can be tailored to display many types of physiological data within the gauge display (see Figure 21).

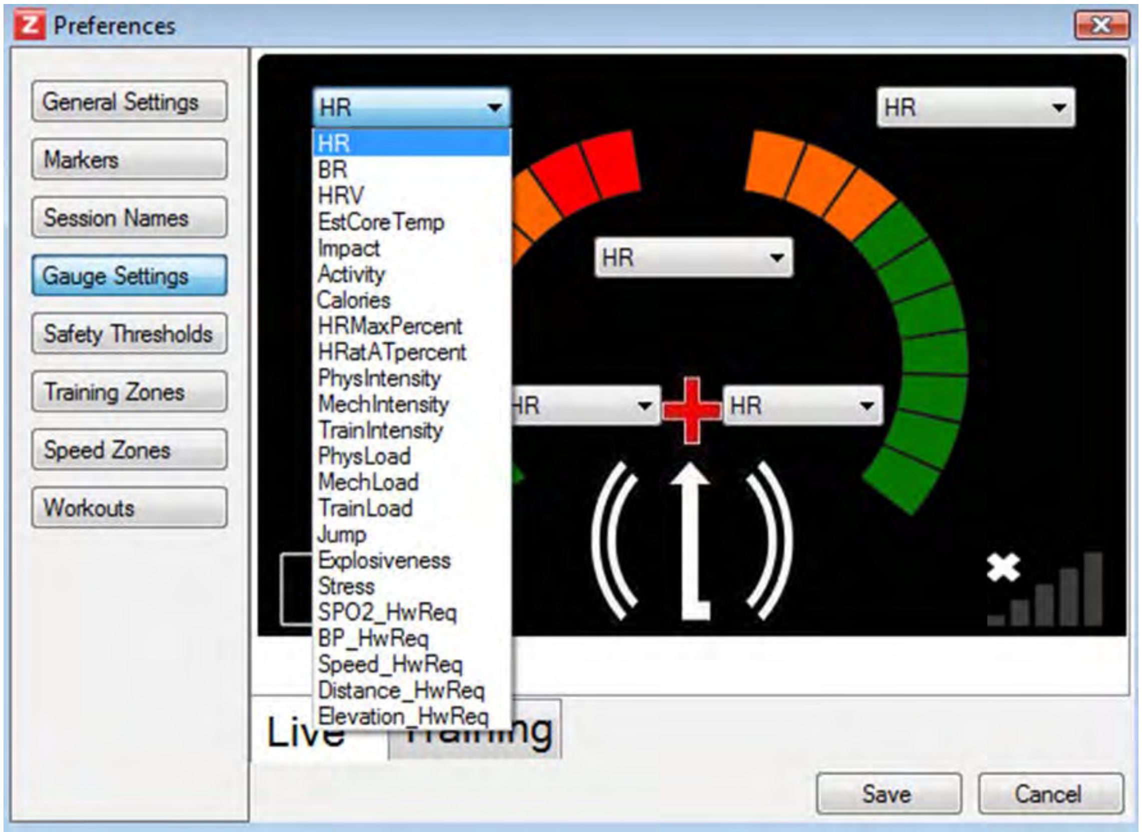


Figure 21. OmniSense gauge settings.

Markers can be manually set during live monitoring for the ease of locating data points to be analyzed later using the second software application, OmniSense Analysis. The four tabs arranged vertically on the right of the application window provide an easily accessible view of the selected sensor's data (Details, Accel, Comms, and Sensors). *Details* provides most of the physiological health data, while *Accel* provides a graphical display of the acceleration forces set upon the sensor (see Figure 22).

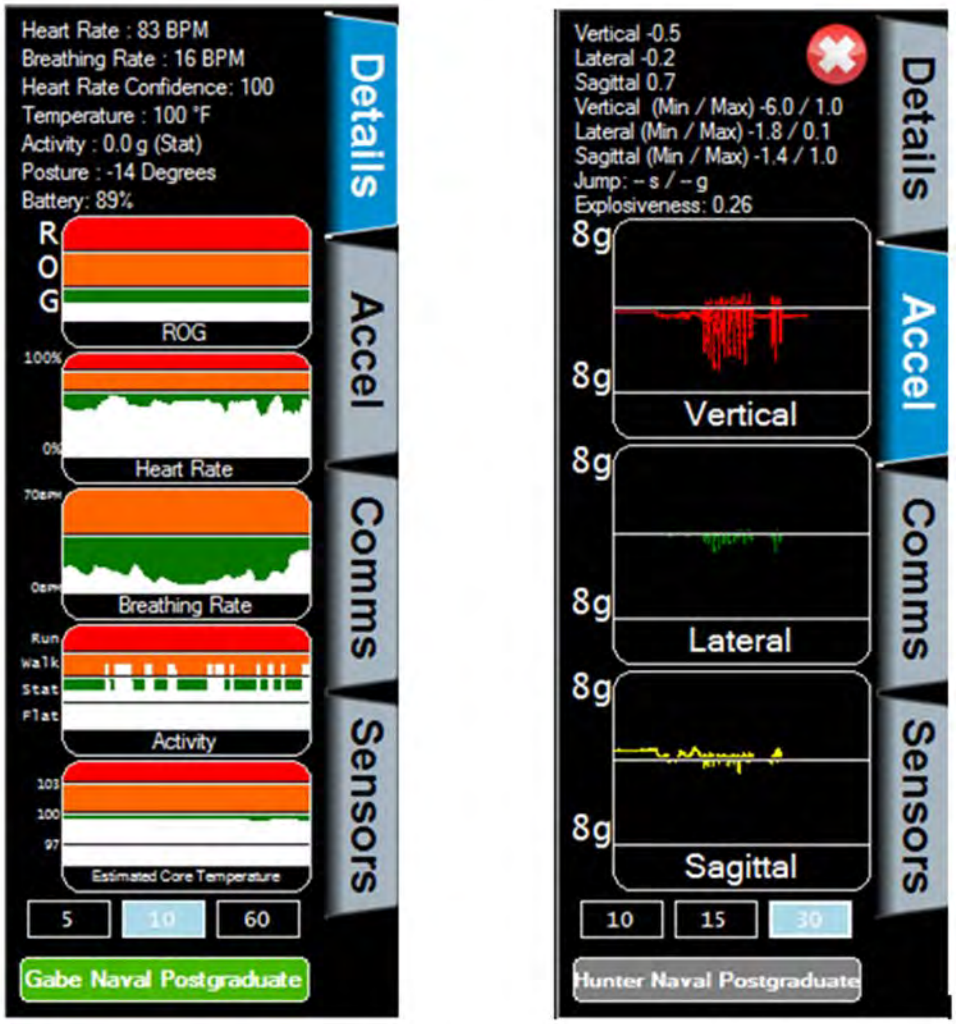


Figure 22. OmniSense Real-Time Vital Signs monitoring.

The other two tabs (not displayed in Figure 22) provide a visual depiction of the communications link and the status of additional sensors that could be attached to the BioHarness 3 module, blood pressure cuff, or a peripheral capillary oxygen saturation (SpO2) sensor.

Although the Zephyr product was not able to connect to the TW-230 radios using TrellisWare's RIDs, it was successful in capturing, storing, transmitting, and displaying vital signs using the 802.15.4 gateway. The OmniSense application was easy to use, and the depth of available viewing options provides a healthcare provider many options on how and what data to display. This allows for a greater variety of use cases for the

BioHarness 3 vital sign monitoring platform to perform in. Further studies are warranted with this product and its performance with Zephyr's proprietary RIDs in order to test the integration within a tactical mesh network.

V. CONCLUSION

The purpose of this study was to explore the current capabilities of COTS sensor technologies for monitoring vital signs. Various COTS sensor systems exist, but exploration into their adaptability into current U.S. Coast Guard and DOD network infrastructure is limited. Due to the unique nature of the U.S. Coast Guard and the DOD, utilization of tactical networked radios within a mesh network for transmission of vital sign data was found to be the most ideal communication platform.

We explored medical vital sign process to determine whether a general need for a technological solution to vital sign capture exists. We discovered through case studies and literature review an overwhelming need to solve two historical problems associated with the vital sign process: limitation of range and transcription of data. Studies advocated the need to automate and make the vital signs process wireless as a solution to these problems in both the civilian and military sectors.

We reviewed various peer-reviewed articles and studies and found a general consensus of what sensor design requirements are needed for future adoption. These requirements center on ease of integration, power-source longevity/miniaturization, and reliability.

Integrating COTS software within U.S. Coast Guard and DOD infrastructure proved challenging. In this study, we chose the Zephyr BioHarness 3 as the our testing case because it operates on the 802.15.1 protocol standard, which would allow for connectivity for wireless transmission to the U.S. Coast Guard's current tactical radio TW-230 to a broader mesh network. The BioHarness 3 was small and lightweight and measured vital signs wirelessly. In our tests, we observed the inability of the TW-230 and the BioHarness 3 to operate in a Bluetooth master mode due to proprietary RID issues. The TW-230's RID were not compatible with the BioHarness 3. Due to financial and time constraints, the proprietary RIDs were not purchased and connectivity to TW-230s was never established. We then explored alternate connectivity options, specifically the use of the Zephyr Gateway 802.15.4 to connect to a mesh network. This configuration was successful and vital sign data was automatically monitored and recorded.

Future Work

The role of the sensor in medicine is quickly becoming more commonplace in the civilian sector. To keep pace, the military sector needs more research into sensor technology to adequately adopt its benefits into the military network infrastructure. Future work in sensor adoption is needed to address software integration, battery longevity/miniaturization, and reliability issues unique to the military environment. While our study was unsuccessful in connecting a COTS sensor to existing military infrastructure (tactical radios), we are confident in the near future the problems associated with acquiring and recording vital signs will be solved.

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